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Published in:
Journal of the Korean Physical Society

Link to article, DOI:
[10.3938/jkps.59.2039](https://doi.org/10.3938/jkps.59.2039)

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Manonara, S. R., Hanagodimath, S. M., Gerward, L., & Mittal, K. C. (2011). Exposure Buildup Factors for Heavy Metal Oxide Glass: A Radiation Shield. *Journal of the Korean Physical Society*, 59(2), 2039-2042.
<https://doi.org/10.3938/jkps.59.2039>

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Exposure Buildup Factors for Heavy Metal Oxide Glass: A Radiation Shield

S. R. MANOHARA*

*Department of Physics, Siddaganga Institute of Technology,
B. H. Road, Tumkur - 572 103, Karnataka, India*

S. M. HANAGODIMATH

Department of Physics, Gulbarga University, Gulbarga - 585 106, Karnataka, India

L. GERWARD†

Department of Physics, Technical University of Denmark, DK-2800 Lyngby, Denmark

K. C. MITTAL

Electron Beam Center, APPD, Bhabha Atomic Research Center, Mumbai-400 085, India

(Received 26 April 2010)

Gamma ray exposure buildup factors for three Heavy Metal Oxide (HMO) glass systems, viz. $\text{PbO-Bi}_2\text{O}_3\text{-B}_2\text{O}_3$, $\text{PbO-B}_2\text{O}_3$, and $\text{Bi}_2\text{O}_3\text{-B}_2\text{O}_3$ glasses are presented. The computations were done by interpolation method using the Geometric Progression fitting formula and ANSI/ANS-6.4.3 library for the energy range from 0.015 to 15 MeV, up to penetration depths of 40 mfp (mean free path). The buildup factors have been studied as functions of incident photon energy and penetration depth. The variations in the buildup factor, for all the glass systems, in different energy regions, have been presented in the form of graphs. Buildup factors of these HMO glasses cannot be found in any standard database, but they are useful for practical calculations in gamma ray shield designs, and they also help to determine and control the thickness of the shielding material used.

PACS numbers: 28.41.Qb, 87.53.Qc

Keywords: Gamma radiation, Interaction of radiation with matter, Buildup factor, G-P fitting formula, Glasses, Radiation shielding, Multiple scattering

DOI: 10.3938/jkps.59.2039

I. INTRODUCTION

As technology advances, there is a constant need to develop materials, which can be used under a hostile environment of high nuclear radiation exposure and can act as a good radiation shield [1]. In this regard, glasses are promising materials because of their homogeneity and range of composition. Typical applications of radiation shielding glasses are in hospital X-ray rooms, radiation therapy rooms, airport security X-ray screens, for materials testing, nuclear facilities, dental clinics, laboratories, X-ray and radiation protection spectacles. Glasses are also used in space technology for protecting human beings and equipment from harmful radiation such as gamma and cosmic rays. Glass has also been suggested for the containment of radioactive waste products.

In general, the Heavy Metal Oxide (HMO) glasses, based on for example PbO or Bi_2O_3 [2-6], have potential applications in radiation shielding, since they have large

absorption cross section for radiation and at the same time small irradiation effects on their mechanical and optical properties. The HMO glasses are better shields to gamma-radiations and may be used as transparent radiation shielding materials [7]. Recently, bismuth based glasses have received attention due to its many potential applications [8,9]. So it becomes a prerequisite to study the interaction of radiation with these glass materials, considering both the primary and the secondary part of the radiation.

The buildup factor helps to determine and control the thickness of the shielding material used. The *exposure buildup factor* is the photon buildup factor in which the quantity of interest is exposure and the detector response function is that of absorption in air.

In the present work, the gamma ray exposure buildup factors were computed using the Geometric Progression (G-P) fitting formula for HMO glass systems, viz. $\text{PbO-Bi}_2\text{O}_3\text{-B}_2\text{O}_3$, $\text{PbO-B}_2\text{O}_3$, and $\text{Bi}_2\text{O}_3\text{-B}_2\text{O}_3$ glasses in the energy range 0.015 – 15 MeV, and up to penetration depths of 40 mfp (mean free path). The generated exposure buildup factor data has been studied as a function of

*E-mail: sr.manohara@yahoo.com

†E-mail: gerward@fysik.dtu.dk

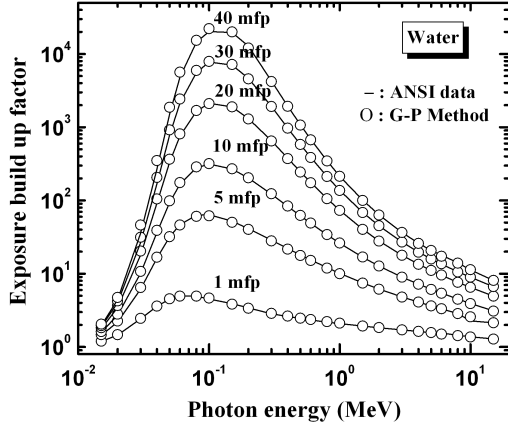


Fig. 1. Exposure buildup factors of water obtained in the present work (circles) compared with those of the ANSI/ANS-6.4.3 standard [15] (solid line) at selected penetration depths (in mfp).

incident photon energy and penetration depth. Buildup factors of these HMO glasses cannot be found in any standard database, but they are useful for practical calculations in gamma ray shield designs.

II. METHOD OF COMPUTATION

The procedure of calculating the buildup factors has been described in detail elsewhere by the authors [10]. In brief, our computational work can be divided into three steps:

1. Calculation of equivalent atomic number, Z_{eq} . [11,12]
2. Calculation of the Geometric-Progression (G-P) fitting parameters using interpolation method. [11,12]
3. Calculation of the exposure buildup factors. [13,14]

The G-P fitting parameters for exposure buildup factors were computed by the process of interpolation using Z_{eq} values. Finally, these G-P fitting parameters were used to generate exposure buildup factors for the present glasses using the G-P fitting formula [13,14]. G-P fitting parameters for the pure elements were taken from the standard reference database, ANSI/ANS-6.4.3 [15].

III. RESULTS AND DISCUSSION

1. Standardization of the procedure

The present method was checked by calculating exposure buildup factors for water in the energy range 0.015 to 15 MeV and up to penetration depths of 40 mfp, and comparing these results with the corresponding ANSI/ANS-6.4.3 data [15]. It can be seen from Fig. 1 that, the present method yields exposure buildup factors for water, which are in excellent agreement with standard data. This gives confidence in our results for the glass materials.

Table 1. Equivalent atomic numbers, Z_{eq} , and exposure G-P fitting parameters for $0.3\text{PbO}-0.6\text{Bi}_2\text{O}_3-0.1\text{B}_2\text{O}_3$ in the energy range 0.015 – 15 MeV.

Energy [MeV]	Z_{eq}	a	b	c	d	X_k
0.015	65.32	0.289	1.003	0.269	-0.3022	23.00
0.030	77.40	0.213	1.008	0.359	-0.0925	16.73
0.040	77.94	0.248	1.016	0.318	-0.0946	14.43
0.050	78.27	0.257	1.028	0.306	-0.1033	14.07
0.060	78.50	0.259	1.039	0.317	-0.1171	14.02
0.080	79.01	0.177	1.486	0.753	-0.1030	15.32
0.100	77.33	0.118	1.835	0.650	-0.1279	21.79
0.150	78.03	0.310	1.330	0.844	-0.0536	16.14
0.200	78.37	0.391	1.181	0.306	-0.1914	13.93
0.300	78.75	0.189	1.157	0.288	-0.0934	13.54
0.400	78.97	0.132	1.204	0.488	-0.0684	14.17
0.500	79.10	0.105	1.254	0.601	-0.0548	14.18
0.600	79.18	0.086	1.293	0.664	-0.0439	13.75
0.800	79.27	0.062	1.353	0.722	-0.0323	13.70
1.000	79.32	0.048	1.389	0.789	-0.0284	13.56
1.500	79.05	0.018	1.388	0.870	-0.0206	14.53
2.000	78.16	0.011	1.405	0.975	-0.0209	13.46
3.000	75.95	0.015	1.400	1.012	-0.0383	13.40
4.000	74.08	0.018	1.363	1.037	-0.0437	13.72
5.000	72.87	0.050	1.408	0.999	-0.0735	13.94
6.000	72.09	0.058	1.427	0.954	-0.0788	14.31
8.000	71.11	0.064	1.537	0.983	-0.0852	14.14
10.000	70.55	0.032	1.580	1.143	-0.0570	14.05
15.000	69.92	0.012	1.750	1.344	-0.0446	13.64

2. Exposure buildup factors of HMO Glasses

The computed exposure G-P parameters for the present HMO glasses are given in Tables 1 - 3. These parameters have been used to get the buildup factor data. The generated data on exposure buildup factors for the present glass materials have been studied as a function of incident photon energy and penetration depths.

Figures 2(a) - 2(c) show the variation of exposure buildup factors as function of penetration depth for some selected photon energies in the energy range 0.015 – 15 MeV. It can be seen that, the buildup factor is almost constant [\cong unity] for all penetration depths at the lowest energy, *i.e.*, 0.015 MeV. At higher energies, the buildup factor increases with increase in penetration depth for all glass materials. This is because more multiple-scattered photons are generated at large penetration depths thereby increasing the buildup factor.

The exposure buildup factors are shown as function of incident photon energy in Figs. 3(a) - 3(c) for some selected penetration depths from 1 to 40 mfp. It can be observed that, buildup factor values are almost constant up to 0.06 MeV, and then suddenly have a peak at about 0.1 MeV. After this, again there are lower values of buildup factors and then their values are steadily increasing with increasing energy. In case of $0.3\text{PbO}-0.6\text{Bi}_2\text{O}_3-0.1\text{B}_2\text{O}_3$ there are two peaks due to the presence of lead and bismuth.

The maximum value of the buildup factor for $0.3\text{PbO}-$

Table 2. Equivalent atomic numbers, Z_{eq} , and exposure G-P fitting parameters for $0.9\text{PbO}-0.1\text{B}_2\text{O}_3$ in the energy range 0.015 – 15 MeV.

Energy [MeV]	Z_{eq}	a	b	c	d	X_k
0.015	65.29	0.289	1.003	0.269	-0.3016	22.95
0.030	77.23	0.212	1.008	0.361	-0.0921	16.85
0.040	77.70	0.248	1.017	0.319	-0.0950	14.39
0.050	77.99	0.258	1.028	0.306	-0.1035	14.07
0.060	78.17	0.259	1.040	0.317	-0.1166	14.03
0.080	44.55	0.782	1.711	0.028	-0.2210	14.76
0.100	77.11	0.120	1.831	0.664	-0.1284	21.41
0.150	77.80	0.312	1.326	0.805	-0.0553	16.08
0.200	78.09	0.388	1.179	0.302	-0.1917	13.91
0.300	78.42	0.188	1.158	0.301	-0.0926	13.55
0.400	78.61	0.131	1.206	0.496	-0.0682	14.17
0.500	78.72	0.105	1.257	0.606	-0.0546	14.17
0.600	78.79	0.086	1.296	0.668	-0.0439	13.75
0.800	78.88	0.062	1.357	0.727	-0.0323	13.70
1.000	78.92	0.048	1.393	0.794	-0.0284	13.55
1.500	78.67	0.017	1.390	0.878	-0.0206	14.51
2.000	77.89	0.010	1.406	0.977	-0.0208	13.45
3.000	75.91	0.015	1.401	1.012	-0.0383	13.40
4.000	74.25	0.018	1.362	1.036	-0.0438	13.73
5.000	73.17	0.050	1.404	1.002	-0.0732	13.94
6.000	72.47	0.058	1.421	0.956	-0.0784	14.31
8.000	71.58	0.064	1.525	0.985	-0.0851	14.15
10.000	71.10	0.032	1.562	1.144	-0.0568	14.06
15.000	70.55	0.012	1.724	1.343	-0.0453	13.64

$0.6\text{Bi}_2\text{O}_3-0.1\text{B}_2\text{O}_3$ [8.91×10^{15}] $0.9\text{PbO}-0.1\text{B}_2\text{O}_3$ [1.97×10^{15}] and $0.9\text{Bi}_2\text{O}_3-0.1\text{B}_2\text{O}_3$ [7.64×10^8] occurs at energies, E_{peak} , equal 0.15 MeV, 0.15 MeV, and 0.1 MeV, respectively, *i.e.*, in the energy range 0.1 MeV – 0.15 MeV. E_{peak} increases slightly with increase in penetration depth, but this is a minor effect. The energy E_{peak} also increases with increasing Z_{eq} of the glass materials. At these energies, Compton scattering is the major photon interaction process, and photoelectric absorption is of relatively low importance, leading to large buildup factors. The large value of the buildup factor is attributed due to the fact that, maximum multiple scattering occurs around this energy region (0.1 – 0.15 MeV) which results in the accumulation of photons, because large numbers of Compton processes are required to degrade the energy of these photons. Therefore, degraded energy photons exist for a longer time, which results in their buildup in the material. Photoelectric absorption has low importance, since these glass materials have high values of effective atomic number, Z_{eff} [7,16]. It is well established that the photoelectric cross-section is proportional to Z^{4-5} and inversely proportional to $E^{7/2}$. It follows that, generally, the photoelectric effect is important for the absorption of low-energy photons, in particular for high- Z materials. Hence, the buildup factor is negligible at low energy region (<0.06 MeV).

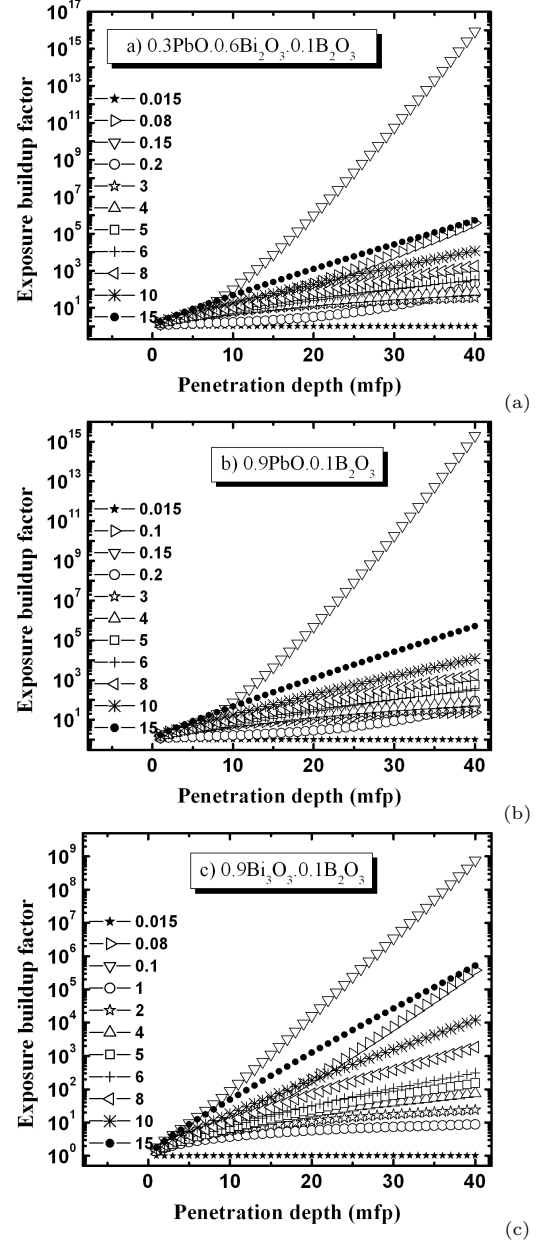


Fig. 2. Variation of the exposure buildup factor with penetration depth (in units of mfp) for some selected photon energies (in MeV): (a) $0.3\text{PbO}-0.6\text{Bi}_2\text{O}_3-0.1\text{B}_2\text{O}_3$, (b) $0.9\text{PbO}-0.1\text{B}_2\text{O}_3$ and (c) $0.9\text{Bi}_2\text{O}_3-0.1\text{B}_2\text{O}_3$.

IV. CONCLUSION

In the present investigation, the G-P fitting formula has been used for calculating exposure buildup factors of HMO glasses. The buildup factors have been found to vary with photon energy and penetration depth.

The results of the present work on HMO glasses cannot be found in any standard database, but they are useful for practical calculations in gamma ray shield designs, and they also help to determine and control the thickness of the shielding material used.

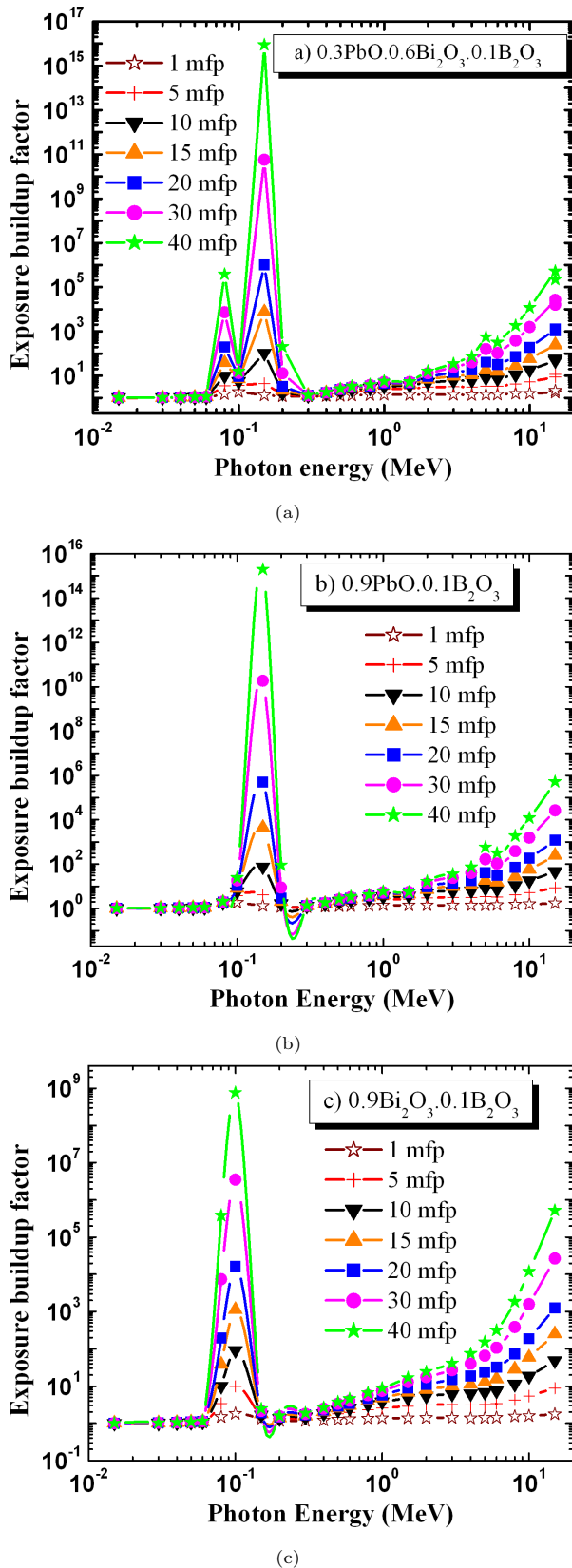


Fig. 3. (Color online) Variation of the exposure buildup factor with photon energy (in MeV) for some selected penetration depths (in units of mfp): (a) 0.3PbO-0.6Bi₂O₃-0.1B₂O₃, (b) 0.9PbO-0.1B₂O₃ and (c) 0.9Bi₂O₃-0.1B₂O₃.

Table 3. Equivalent atomic numbers, Z_{eq} , and exposure G-P fitting parameters for 0.9Bi₂O₃-0.1B₂O₃ in the energy range 0.015 – 15 MeV.

Energy [MeV]	Z_{eq}	a	b	c	d	X_k
0.015	65.33	0.293	1.003	0.269	-0.3023	23.01
0.030	77.45	0.213	1.008	0.359	-0.0926	16.48
0.040	78.00	0.248	1.016	0.318	-0.0944	13.78
0.050	78.33	0.257	1.027	0.306	-0.1032	14.51
0.060	78.57	0.259	1.039	0.318	-0.1172	14.18
0.080	79.00	0.177	1.486	0.754	-0.1029	15.31
0.100	77.38	0.117	1.836	1.142	-0.1277	15.02
0.150	78.08	0.309	1.331	0.253	-0.0532	22.72
0.200	78.44	0.392	1.181	0.197	-0.1913	15.62
0.300	78.83	0.190	1.156	0.447	-0.0936	13.93
0.400	79.05	0.132	1.204	0.576	-0.0685	13.72
0.500	79.19	0.105	1.253	0.647	-0.0548	14.17
0.600	79.27	0.086	1.292	0.697	-0.0439	14.03
0.800	79.37	0.062	1.352	0.771	-0.0322	13.76
1.000	79.41	0.048	1.389	0.824	-0.0284	13.58
1.500	79.14	0.018	1.387	0.954	-0.0206	13.89
2.000	78.22	0.011	1.404	0.995	-0.0209	14.08
3.000	75.96	0.015	1.400	1.019	-0.0383	13.44
4.000	74.04	0.018	1.363	1.037	-0.0437	13.72
5.000	72.80	0.051	1.409	0.958	-0.0736	14.13
6.000	72.00	0.058	1.428	0.954	-0.0789	14.31
8.000	70.99	0.064	1.540	0.983	-0.0852	14.14
10.000	70.42	0.032	1.584	1.143	-0.0570	14.05
15.000	69.78	0.012	1.755	1.344	-0.0444	13.64

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